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Magnet Division Specification

Superconducting Magnet Division

Specification Number: SMD-APUL-2003

Revision: A

Procurement Specification, Nb-Ti Wire for APUL Dipole Magnets

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Revision History

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1. Scope:

This specification establishes the requirements for the manufacture, inspection, test, identification and delivery of Nb-Ti superconductor wire used to fabricate Rutherford-type cable for use in D1 Beam Separation Dipole Magnets under the APUL project.

The main emphasis of the specification is on adherence to a uniform production method for the conductor. The goal is to have the magnetic field behavior of all magnets be identical and, because of the effects of conductor magnetization and its possible time dependence, it is imperative that conductor be fabricated using materials with the same specifications and processes with the same steps, parameters and tolerances throughout each phase of the production. Therefore, the production phase of the procurement will be completed by one vendor with strict adherence to that vendor's process; no process changes will permitted during the production phase.

Wires will be selected for use in cable using critical current measurements made by the vendor. Selection will begin after a minimum amount of the production is available.

The vendor will be responsible for checking all wire dimensional, mechanical and electrical parameters. BNL will make additional measurements to verify the wire properties.

2. Applicable Documents:

The following documents in effect on the date of invitation to quote form a part of this specification to the extent specified herein:

- ASTM F68-82 Standard Specification for Oxygen-Free Copper in Wrought Forms for Electron Devices - for classification requirements (Plate 1).
- ASTM B170-89 Standard Specification for Oxygen-Free Electrolytic Copper-Refinery Shapes - chemistry requirements governed by B170
- RHIC-MAG-M-4000 Niobium-Titanium Alloy Bars and Rods
- RHIC-MAG-M-4001 Barrier Grade Niobium Sheet
- BNL-QA-101 Brookhaven National Laboratory Seller Quality Assurance Requirements

3. Requirements:

3.1 Raw Material: Raw material used in the manufacture of Nb-Ti composite wire shall be procured to the applicable requirements of this specification and inspected/tested by the vendor for conformance to those requirements before release for production use.

3.1.1 Nonconforming Raw Material: Material found to deviate from requirements shall not be dispositioned through any seller review process for production use without prior, specific written approval from BNL.

3.1.2 Raw Material Identification: Each lot of wire raw material shall be uniquely identified to allow all vendor manufacturing, test, and inspection records for finished wire to be traceable to the original lot of raw material.

3.2 Technical Properties

3.2.1 Conductor Type: The conductor shall be a composite of Nb-Ti filaments in an oxygen-free copper matrix.

3.2.2 Conductor Billet Components: The components described below shall be used to fabricate the superconductor.

3.2.2.1 Niobium-Titanium Alloy: The alloy composition shall be high homogeneity grade or BNL-approved equivalent. It must be purchased by the vendor to meet the requirements of the specification RHIC-MAG-M-4000. The composition tolerance covers all Nb-Ti bars to be used to fill the order.

3.2.2.2 Copper: With the exception of the billet end caps, all copper raw material purchased by the vendor to be used for billet fabrication shall meet the chemistry requirements of ASTM B170-89, and have residual resistance ratio (RRR) greater than 250:1. This copper, when finally used for the billet cans, shall be wrought, not cast, and shall meet the classification requirements of ASTM F68-82, Class 2 or better. The copper used for the billet end caps shall be wrought, not cast.

3.2.2.3 Niobium Material for Diffusion Barrier Construction: Niobium must be purchased by the vendor to meet the requirements of the specification RHIC-MAG-M-4001.

3.2.3 Conductor Fabrication: The procedures listed below must be followed during billet assembly or processing and cabling.

3.2.3.1 Monofilament Shape: The monofilament rods used to assemble the multifilament billet shall have hexagonal cross section.

3.2.3.2 Diffusion Barrier Construction: A niobium diffusion barrier shall be placed between the Nb-Ti and the copper in the monofilament billet. Its thickness and quality shall be sufficient to prevent formation of copper-titanium compounds during wire fabrication.

3.2.3.3 Filament Array: The design of the overall placement of filaments inside the billet shall be submitted to BNL for approval with the bid package. There shall be a copper island in the center of the billet; it shall comprise a minimum of 10% of the total area of the final wire.

3.2.3.4 State of Wire Anneal: The wire shall be fabricated in the cold-worked condition for cabling (i.e. with no final anneal). The electrical parameters R(295) and RRR given in this specification reflect these conditions.

3.2.3.5 Production With No Deviations: The specification for Nb-Ti, copper and Nb materials used for wire manufacturing shall be the same throughout the production. Also, the production steps, parameters and tolerances for the wire fabrication shall remain the same during the production phase.

3.2.3.6 Production Unit: All superconductor wire produced to this specification shall be processed in "production units".

A "production unit" consists of material from a common multifilament billet which undergoes identical mechanical and thermal processing, and shall be identified as such. A "production unit" may be less than one full billet. All material from a "production unit" shall be thermally cycled together in the same furnace, for each and every heat-treatment.

Work-In-Process material from a "production unit" shall remain physically grouped together throughout all phases of the manufacturing process. Any portion of a billet which becomes separated from its "production unit" shall be considered non-conforming and shall be addressed as such.

3.2.3.7 Control of Manufacturing Machines and Methods: The machines and equipment used to process all superconductor made to this specification shall be identified for BNL and documented as part of the vendor's Quality Plan. No changes to machines, methods or processes shall be permitted without prior written approval of BNL.

3.2.3.8 Frequency of Sample Testing: The expected frequency of wire sample testing by the vendor and by BNL is summarized in Appendix A. The transmittal of the data and samples to BNL is given in paragraphs 4.2, 4.3, and 4.4 for the wire.

3.2.3.9 Manufacturing Data: BNL does not require regular transmittal of manufacturing data related to wire fabrication. These data can be audited regularly by BNL staff at the vendor facility. The vendor must maintain manufacturing data records for two (2) years after the date of acceptance of the cable by BNL.

3.2.4 Wire Performance Requirements: The superconductor wire must meet the Performance requirements described in Tables I and II and explained in subsequent paragraphs. Checks of the wire dimensional, mechanical and electrical requirements are the responsibility of the vendor. A 10 ft. long wire test specimen, which is adjacent to the location used for each vendor wire electrical test, shall be delivered to BNL; see paragraph 4.4. The frequency of wire sample testing is given in Appendix A.

Table I. Wire Dimensional and Mechanical Requirements

Requirement	Value	Defined in Para. No.
Nominal Filament Diameter	6μm	3.2.4.1
Minimum Filament Spacing	1μm	3.2.4.1
Nominal Copper-to-Non-Copper Ratio	1.80:1	3.2.4.2
Nominal Number of Filaments	4100 to 4200	3.2.4.3
Wire Diameter	0.648±0.003 mm	3.2.4.4
Wire Twist Direction	Right	3.2.4.5
Wire Twist Pitch	13±1 mm	3.2.4.5
Wire Sharp Bend Test	No Damage	3.2.4.6
Wire Springback Test	<1090 degrees (horiz.) <1200 degrees (vert.)	3.2.4.7
Wire Surface Condition	No defects	3.2.4.8
Wire Minimum Length	4,000 ft.	3.2.4.9

Table II. Wire Electrical Requirements

Requirement	Value	Defined in Para. No.
Wire Minimum Critical Current at 5.6T	269A	3.2.4.10, 3.2.4.11
Variation of Measured Wire Critical Current at 5.6T	±10% maximum limit	3.2.4.10, 3.2.4.12
Wire Maximum R(295)	0.0827 ohms/m	3.2.4.13
Wire Minimum RRR	36	3.2.4.13

3.2.4.1 Nominal Filament Diameter and Spacing: The nominal filament diameter and spacing shall be defined by the billet design. Before fabrication, the vendor shall submit to BNL for written approval a drawing showing the billet assembly and dimensions to demonstrate that the nominal filament diameter and spacing shall be obtained at the final wire size. Shaving of the external copper during billet processing must be considered in the demonstration.

3.2.4.2 Nominal Copper-to-Non-Copper Ratio: The nominal value of the ratio of copper volume to non-copper volume is 1.80:1. However, to simplify measurement there is no technical requirement for this parameter. Instead there will be a technical requirement for R(295), for RRR and for the wire diameter. The calculated copper-to-non-copper ratio will be greater than 1.70:1 provided that the wire diameter is within the specified tolerance, R(295) is less than a maximum and RRR is greater than a minimum value. The procedure for determining this ratio by electrical measurement will be finalized when R(295) and RRR are known from the state of the wire anneal. See Appendix B for a description of this method.

3.2.4.3 Number of Filaments: The vendor shall choose the number of filaments for the production to be within the range specified in Table I. This chosen number shall remain fixed throughout the production within a tolerance of ± 20.

3.2.4.4 Wire Diameter: The tolerance on the wire diameter is a maximum limit and does not include averaging or statistical weighing. The tolerance must be held for the wire measured across any diameter/axis. Verification of this diameter shall be determined by the vendor using an appropriately calibrated laser micrometer used to check all of the wire produced. The laser micrometer should be capable of detecting local variations in the wire diameter over a length of 12 mm. Statistical analysis of laser micrometer measurements shall be provided by the vendor to BNL.

3.2.4.5 Wire Twist Direction and Pitch: All wire shall be right-twist so the filaments follow the same rotation as a right-hand screw thread. The wire is to be twisted before the final sizing die. Requirements on twisting shall apply over the full length of the delivered wire. No leaders with variable twist are allowed. The vendor shall submit to BNL for approval a method to assure Quality Control of the parameters for wire twist direction and pitch.

3.2.4.6 Wire Sharp Bend Test: The superconductor wire shall meet the sharp bend test requirements with no visible damage to the copper or to the filaments after etching. The test procedure is described in Appendix B.

3.2.4.7 Wire Springback Test: The superconductor wire shall meet the requirements of a springback test following the test procedure described in Appendix B, with the fixture mounted on a horizontal surface. If the fixture is mounted on a vertical surface, with wire and weight hanging freely, the maximum acceptable value shall be as given in Table I.

3.2.4.8 Wire Surface Condition: The wire surface shall be free of all surface defects, slivers, folds, laminations, dirt, or inclusions. No filaments shall be visible. These conditions must be met for any sample of the wire inspected using a magnification of 10x.

3.2.4.9 Wire Minimum Length: A minimum length requirement is imposed to assure high quality of the wire and its fabrication process. Length shall be determined after all lead and end defects have been removed by cropping. These defects include areas of distorted cross section due to wire pointing by swaging, foreign material attached as a temporary leader, or areas of distorted filaments that occur at the start and end of an extrusion. A continuous compilation of wire lengths must be made by the vendor and available to BNL on request.

3.2.4.10 Wire Critical Current Determination: The critical current values refer to a test temperature of (4.22 ± 0.01)K and a critical current criterion of $\rho = 1x10^{-14}$ ohm -m, based on the wire cross section area and with the applied magnetic field (given in Table II) perpendicular to the wire axis. The tolerance on the magnetic field is ± 0.01T. No correction is made for self-field effects.

The critical current test procedure given in Appendix B is to be used. Although it is not included as a technical requirement, the Quality Index ,n, is to be reported by the vendor with every critical current measurement. This parameter is described in Appendix B. It is required that under the test conditions the quench current, I_Q, be greater than the critical current. I_Q is also to be reported by the vendor. I_c at $1x10^{-13}$ ohm·m may be reported by the vendor in lieu of determining I_Q; the choice must be communicated to BNL.

3.2.4.11 Wire Minimum Critical Current at 5.6T: The wire minimum critical current in Table II and the conditions defined in paragraph 3.2.4.10 correspond to a

current

density in the non-copper region of the wire of 2600 A/mm^2 at 5.0T, 4.22K,

a

nominal copper-to-non-copper ratio of 1.80:1, a wire diameter of 0.648 mm and $I_c(5.6)/I_c(5.0) = 0.88$. No correction is made for self-field effects. Any wire not meeting this requirement will be rejected.

3.2.4.12 Variation of Measured Wire Critical Current at 5.6T: The variation of the measured wire critical current at 5.6T shall remain within the given maximum limit from the running average throughout the entire production. Any wire with critical current outside this range will be rejected.

3.2.4.13 Wire Maximum R(295) and Minimum RRR: The resistance of the wire at (295.0 ± 0.2)K is referred to as the room temperature normal state resistance. It is an important parameter for magnet construction and depends primarily on the content and purity of the copper. The procedure for measuring R(295)described in Appendix B is to be used.

The resistance of the wire just above the Nb-Ti superconductor transition temperature and at zero field is termed R(10). The procedure for measuring R(10) described in Appendix B is to be used. The wire residual resistance ratio or RRR is given by the ratio R(295)/R(10).

4. Quality Assurance Provisions:

The vendor shall maintain a quality assurance program to insure that each item offered for acceptance or approval conforms to the requirements herein.

4.1 Requirements of BNL-QA-101

4.1.1 The vendor shall accomplish the following requirements of BNL-QA-101, Brookhaven National Laboratory Seller Quality Assurance Requirements:

Paragraph in BNL-QA-101

3.1 including 3.1.2
3.2
3.3
3.5
3.6
3.7
4.1
4.2
4.3
4.4 including 4.4.1, 4.4.2, 4.4.3, but 30 days before first billet assembly
4.5

4.6 but 30 days before first billet assembly
4.7 including 4.7.1, and 4.7.2, 4.7.3
4.10 including 4.10.1, 4.10.2, 4.10.3, 4.10.4
4.12

4.13
4.15
4.16
4.19 but no changes allowed
4.21
4.23

4.1.2 BNL does not grant the Seller material review authority to accept as-is items that do not conform to the requirements of this procurement, or to repair items to a still nonconforming condition.

4.1.3 In the event of conflict between this specification and BNL-QA-101, this specification shall take precedence.

4.2 Data Transmittal: The vendor shall complete and submit to BNL wire measurement data as given in Appendix C. Electronic data transmittal to BNL is required. An acceptable format will be agreed to by BNL and the vendor.

4.3 Wire Measurement Data and Samples: The frequency of wire measurements is given in Appendix A. The data shall be submitted in electronic form to BNL for information purposes approximately one week in advance of shipment.

4.4 Wire Samples: Ten ft.-long wire samples will be taken from every wire spool and sent to BNL. If that wire spool is one of those selected by the vendor for measurements as described in Appendix A, the sample shall be taken adjacent to the location used for each vendor wire electrical test.

5. Preparation for Delivery:

5.1 Packaging: Spools of cable shall be packaged and secured to pallets and wrapped to assure adequate protection against dirt, chips, the elements, and handling damage.

5.2 Marking/Requirements: Spools and exterior packaging shall be identified with the following information in the order shown:

"Superconductor Wire for APUL Dipole Magnets"
Specification No. SMD-APUL-2003, Rev. A
BNL P.O. No. ________________________
Wire ID______________________________
Length __________ feet
Gross Weight __________ pounds
Net Weight ____________ pounds
Tare Weight ____________ pounds
Date of Manufacture
Name of Manufacturer

Marking labels shall be applied so they are visible on each spool flange and on the top surface.

5.3 Wire Identification Numbers: The system for wire identification will be given by BNL to the vendor.

APPENDIX A
FREQUENCY OF SAMPLE TESTING

I. Wire Testing

A. Reference:

Table I.Wire Dimensional and Mechanical Requirements.
All measurements to be completed by the vendor.

Requirement	Test Frequency
Nominal Filament Diameter and Spacing	Demonstration from billet design
Number of Filaments	Vendor QC
Wire Diameter	Continuous laser micrometer measurements
Wire Twist Direction and Pitch	Vendor QC
Wire Sharp Bend Test	Min. four samples from each prod. unit or 25%, whichever is greater
Wire Springback Test	Vendor QC
Wire Surface Condition	Vendor QC
Wire Minimum Length	Vendor QC

APPENDIX A (Cont'd)

I. Wire Testing (continued)

B. Reference: Table II. Wire Electrical Requirements.
All measurements to be completed by the vendor.

Note: A wire test specimen shall be delivered to BNL which is adjacent to the location used for each vendor wire electrical test. Also see paragraph 4.4

Requirement	Test Frequency
Wire Critical Current at 5.6T - to satisfy minimum and variation requirements	Min. four samples from each prod. unit or 25%, whichever is greater
Wire Maximum R(295)	Min. four samples from each prod. unit or 25%, whichever is greater
Wire Minimum RRR	Min. four samples from each prod. unit or 25%, whichever is greater

Definitions for Wire Testing:

1) A "spool" consists of a continuous (unbroken) length of wire.

2) A "production unit" consists of wire from a common multifilament billet, which goes through identical mechanical and thermal processing.

3) Where a specified number of samples are to be tested from a "production unit", these specimens must be selected from widely separated portions of the "production unit".

4) "Vendor QC" indicates that the Quality Control (QC) of the parameter is the responsibility of the vendor. The vendor must initiate a program to assure control of the parameter within the required tolerance.

5) In order to assure confidence in results from wire sample measurements, in case there is a large number of "spools", it is necessary to require a minimum of four samples be tested from each "production unit" or 25% of the number of "spools", whichever is greater.

APPENDIX B
SUPERCONDUCTOR WIRE TEST METHODS

Test Method 1. Wire Sharp Bend Test

Test Method 2. Wire Springback Test

Test Method 3. Verification of Electrical Properties of Superconducting Wire

A. Wire Critical Current Determination

B. Wire R(295)and RRR Determination

Test Method 1. Wire Sharp Bend Test

1. Purpose:

The purpose of this test is to approximately simulate the deformation to the superconductor wire that may occur during cabling. The sharp bend fixture is made to produce 20% deformation for the wire diameter used.

2. Materials Required:

A 3-inch long sample of wire to be tested

3. Test Equipment:

Wire Sharp Bend Test Fixture or equivalent.

4. Applicable Documents:

None

5. Test Procedure:

5.1 Bend the wire sample in half and place the bend in the slot of the fixture.

5.2 Slide the mating top of the fixture in the slot and squeeze the sample halves together with a bench vise until closed.

5.3 Remove the top of the fixture and loosen the side screw.

5.4 The sample now resembles a hairpin. Examine the bend under 10x magnification to determine if the wire is cracked or deformed. Any indication of cracking or unusual deformation is cause for rejection and must be brought to the attention of BNL.

5.5 Etch the sharp bend sample while stress-free in nitric acid. USE ALL APPLICABLE PRECAUTIONS IN HANDLING ACIDS. Examine the sample again with 10x magnification to determine possible filament damage. Any indication of filament damage is cause for rejection and must be brought to the attention of BNL.

<u>Test Method 2. Wire Springback Test</u>

1. <u>Purpose</u>:

This test establishes a standardized method for testing superconductor wire to determine its springback acceptability for cabling.

2. <u>Materials Required</u>:

A 3-1/2 ft. length of superconductor wire to be tested.
Note: Do not bend wire unnecessarily.

3. <u>Test Equipment</u>:

3.1 Springback Test Fixture or equivalent (Fig. 1).

3.2 (5.0 ± 0.2) pound weight.

4. <u>Applicable Documents</u>:

None.

5. <u>Test Procedure</u>:

5.1 Prepare one end of wire sample with a 1/2 inch long, right-angle bend and tie the other end securely to a 5-pound weight.

5.2 Test the springback fixture to be sure it turns freely.

5.3 Thread the right-angle bend through the test fixture and place in the hole in the spring winder with the locking pin in place.

5.4 Tighten the wire.

5.5 Make sure the right-angle bend is not affecting the "0" reading and the wire is tangent to the spring winding shaft.

5.6 Set "0" on the degree wheel.

5.7 Hang the 5-pound weight over the end of the table. Release the clamp. Hold the spring winder handle and pull the locking pin.

5.8 Wind 10 complete turns and replace locking pin. Then tighten wire clamp.

5.9 Hold spring handle and remove locking pin. Gently let the spring unwind and note the number of revolutions.

5.10 Once the spring has stopped, gently touch the spring handle to make sure the spring has equalized and reached its full springback. Do not unwind the spring.

5.11 Note and record the total number of degrees of springback.

5.12 Cut the sample at the wire clamp and the right-angle bend.

5.13 Carefully slide the spring winder out of its bearings and remove the sample.

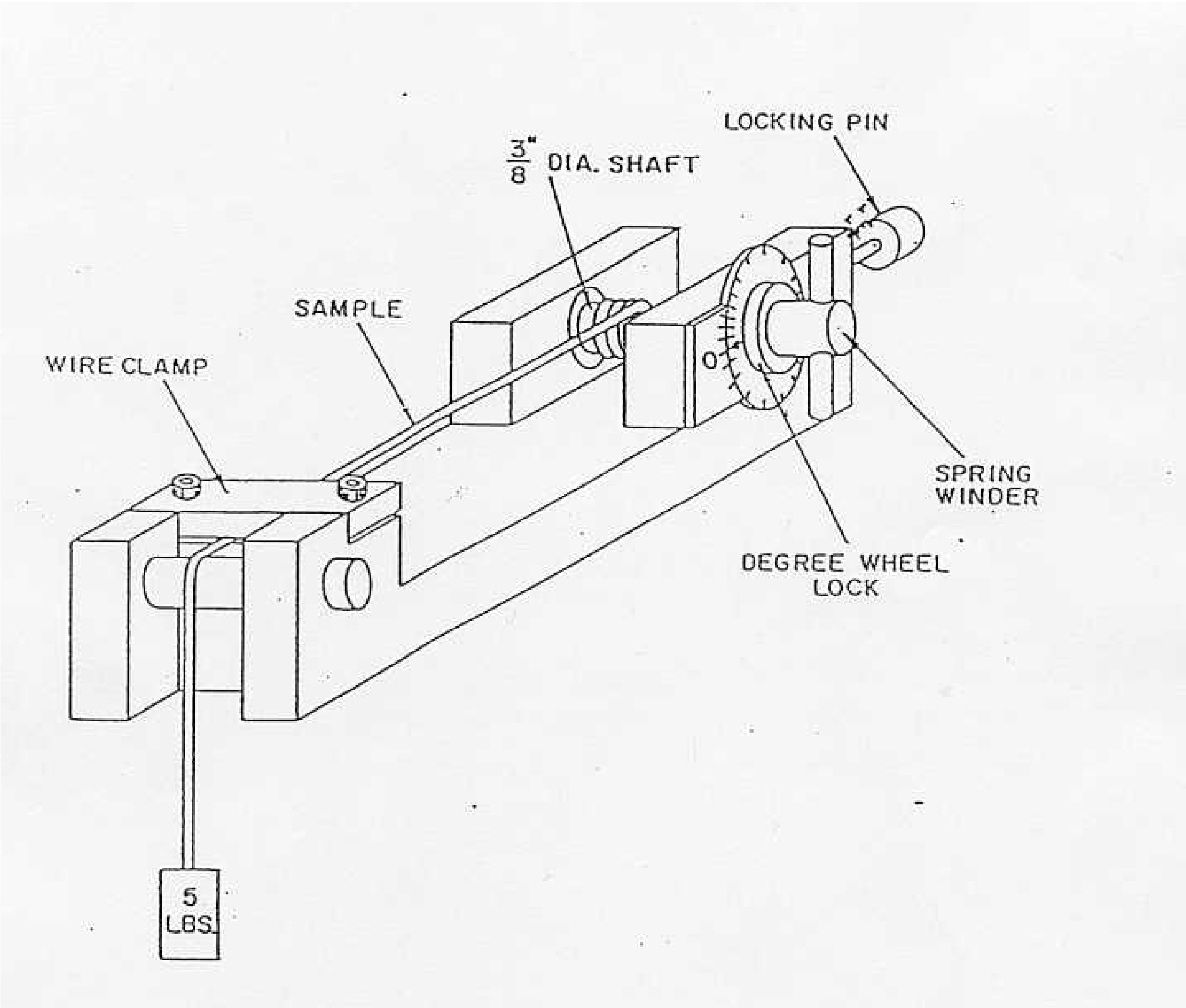

Fig. 1. Spring-back Test Fixture.

Test Method 3. - Verification of Electrical Properties of Superconducting Wire

A. Wire Critical Current Determination

1. General Outline: Definition of Critical Current

The V-I curve is determined as a function of increasing current until an irreversible transition or quench occurs. This measurement is normally carried out in the specified external field at 5.6T applied normal to the wire axis, and in a temperature bath of liquid helium at 4.2K. No correction is made for self-field effects. For currents less than the quench current the V-I curve is reversible.

The critical current, I_c, is defined as that at which the resistance per unit length, R, is:

$$R = 10^{-14} /(\pi d^2/4), \text{ ohms/m}$$

where d is the wire diameter in meters. The effective resistivity of the wire is 10^{-14} ohm · m at the critical current.

2. Sample Testing

The vendor shall measure the critical current for samples of wire at the specified field value and T = 4.2K. If a temperature of 4.2K is inconvenient, measurements may be made at another temperature and a conversion formula must be supplied. The conversion formula must be approved by BNL. [The notation used here for temperature is as follows: t-in degrees Celsius, T-in degrees Kelvin.]

3. Sample Mounting

The sample wire is most conveniently mounted on a cylindrical grooved form which is made of an insulator, such as G-10, and which fits in the bore of a solenoid magnet.(See Section 4 below). The monofilar arrangement, Fig. 2, is used; this lends itself to multiple sample mounting if desired. Voltage taps are arranged as in Fig. 2. Means must be provided for constraint of mechanical motion without interfering with coolant contact: use of a G-10 form with grooved location of wire and careful tensioning during mounting is recommended. Care must be taken to ensure that a temperature gradient is not introduced into the region of measurement (gauge length). Care must also be taken in bending the samples, especially at the end of a bifilar sample.

4. Procedure (See Fig. 2.)

The sample length (between voltage taps) should be > 25 cm. This corresponds, typically, to a voltage drop of several microvolts at I_c. This is readily measured with the aid of a suitable preamplifier or digital voltmeter. Samples of shorter length may be used if a well functioning nano-volt detection system is available. Equipment must be capable of determining the effective resistivity to a precision of 10%.

The voltage signal can be recorded on an X-Y recorder, but digital data acquisition is preferred. The V-I curve may be taken either point-by-point (current constant for each measurement) or continuously if induced signals due to ramping are not too large or noisy. When the V-I curve is determined by the latter procedure, care must be taken to ensure that there is no rate effect for the ramp rate used. Typically, current is supplied by a stable, well-filtered power supply. The current should be measured to a precision of ± 0.5%. Use of a low resistance normal metal shunt connected across the sample is permitted provided the resulting correction for shunt current is accurately known and is <0.1%. Electronic circuitry for quench protection is preferable.

It is highly desirable that the Quality Index (n) be estimated using the equation $V = \text{constant} \cdot I^{n+1}$. Data points corresponding to ρ-values less than 10^{-14} ohm·m will usually be less accurate than those for which ρ is greater than this value. Above 10^{-13} ohm·m resistive heating may cause the observed voltage values to be too large. Hence, in fitting a straight line to the log-log plot of the data, the region corresponding to $10^{-14} \leq \rho \leq 10^{13}$ ohm·m should be emphasized.

5. Magnetic Field

The external field is most conveniently applied by means of a superconducting solenoid. The field must be uniform over the sample reference length to ± 0.5%. The direction between field and wire axis must be $90^o \pm 6^o$ everywhere. This range of angles corresponds to an estimated variation in I_c of <0.5%.

6. Temperature Bath Correction

The specification temperature is 4.22K, that of boiling helium at standard atmospheric pressure. The bath temperature must be recorded with the aid of appropriate thermometry (cryogenic thermometer or vapor pressure of bath) with a precision of ± 0.010K (10mK). Deviations of 25mK or less from 4.2K correspond to an error in I_c of 1% or less and may be ignored. For larger temperature excursions the "linear T" type of correction should be applied:

$$\frac{I_c}{I_t} = \frac{T_c - 4.22}{T_c - T}$$

where T_c is the transition temperature at the specified magnetic field. (T_c = 6.9K at 5.6T.) I_t is the current measured at temperature T, and I_c is the critical current at the specification temperature.

B. Wire R(295) and RRR Determination

1. General Outline: Definition of Residual Resistance Ratio

This method covers the measurement of electrical resistance of Nb-Ti multifilamentary composite wire which is used to make high current superconducting cables. The composite matrix is copper. The resistance per meter is determined at room temperature (295K) and just above the superconductor transition temperature (T_c ~ 9.5K). These quantities are designated R(295) and R(10), respectively, and are measured with an accuracy of 0.5%. The ratio R(295)/R(10) is defined to be the residual resistance ratio, RRR.

R(295) is determined chiefly by the copper matrix. For a given wire diameter it provides a measure of the copper-to-non-copper volume ratio.

R(10) is determined chiefly by the residual resistance of the copper matrix and R(295). The ratio RRR provides a measure of the electronic purity of the copper matrix.

2. Apparatus Description

A four-wire method is used to determine the resistance. The wire sample is mounted on a probe which is also used for superconducting critical current measurements. It has leads which are suitable for carrying the required current from room temperature into a liquid helium bath, and potential leads for measuring the voltage drop across a measured length of the test specimen. The probe should be mounted so that the test specimen can conveniently be raised and lowered through the level of a helium bath.

Voltage drops are measured with a voltmeter of 0.5 μV resolution. It is helpful during the low temperature measurement to use an X-Y recorder simultaneously with the digital voltmeter, with Y set to voltage and X to time. (See Section 4)

Currents in the range 0.1 to 1.0A for the R(295) determination and 1 to 10A for the R(10) determination are provided by a well regulated and filtered DC power supply. The current is measured by means of a shunt of 0.25% accuracy.

A thermometer of sensitivity 0.1^{o}C is conveniently used for this purpose as an uncertainty of 1^{o}C is not accurate enough to determine the copper-to-superconductor ratio to ±0.01.

3. Sample Mounting

The test specimen is wound on a grooved form. The ends are soldered to the copper terminations of the current leads over a minimum length of 1 inch. Voltage taps are soldered to the specimen at a distance of a least 1 inch from the current joint. Voltage taps are soldered to the specimen at a separation distance of at least 1 inch from each current lead connection. It is advisable that these taps be in the form of fixed pins so that the test length be constant throughout a series of measurements. In order to assure an accuracy of 0.2% in length this length should be ~ 25 cm or more. The voltage leads should follow the sample in a non-inductive fashion so as to minimize noise pickup. Alternatively, the sample may be wound non-inductively on the form.

4. Procedure

Room temperature measurements are made at currents which are a compromise between the requirements of sensitivity and negligible ohmic heating. A typical value is 0.5A. Voltage readings are taken for forward and reversed current and averaged.

Low temperature measurements are made in a helium dewar. The probe is raised so that the lowest point of the specimen is a few centimeters above the liquid helium bath level while measuring current is flowing. After a time of order one second the sample warms above T_c(~ 9.5K) and the voltmeter reading suddenly jumps from zero to a finite value corresponding to the sample's normal state resistance. The latter is substantially independent of temperature from the transition temperature, T_c, to 15K (residual resistance region), so that the voltage remains constant long enough to be read. When the X-Y recorder is used, a series of abrupt voltage changes are recorded as the specimen is alternately raised and lowered through the helium bath level. The height of these steps should be reproducible.

5. Room Temperature Correction

If the measurements are made at room temperature the differences from 295K necessitate a temperature correction. Designating the observed resistance as R and the ambient temperature as t(^oC), the resistance at the reference temperature of 295K is calculated as follows:

$$R(295) = R/[1 + 0.0039\ (t - 22)]$$

The effect of the Nb-Ti is negligible for the purpose of this correction.

6. Cu/SC Ratio Calculation

The copper: superconductor volume ratio (x) is calculated from R(295) and RRR by means of the formula

$$x = \frac{1 - R(295)\,A/\,\rho_s}{R(295)\,A/\,\rho_{Cu} - 1}$$

where R(295) = resistance of the cable at 295K in ohms/m

ρ_{Cu}= resistivity of the copper at 295K, in ohm · m

$= \rho_i \dfrac{RRR}{RRR - 1}$

ρ_i= resistivity of pure copper at 295K

$= 1.695 \times 10^{-8}$ ohm · m

ρ_s= resistivity of Nb-Ti at 295K

$= 60 \times 10^{-8}$ ohm · m

and A = wire cross section area in m^2

$= \pi d^2/4$ (d = wire diameter in m)

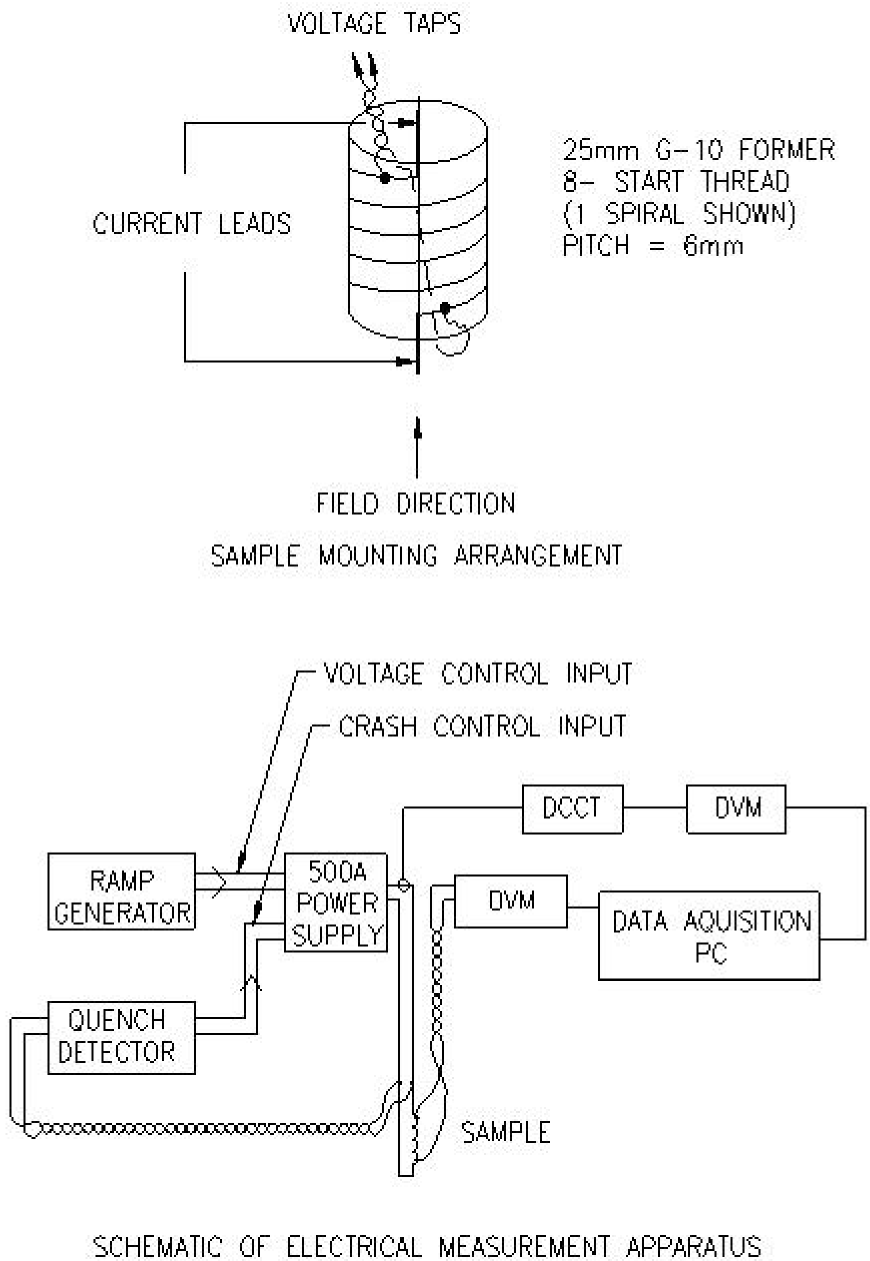
VOLTAGE TAPS
CURRENT LEADS
25mm G-10 FORMER
8- START THREAD
(1 SPIRAL SHOWN)
PITCH = 6mm
FIELD DIRECTION
SAMPLE MOUNTING ARRANGEMENT
VOLTAGE CONTROL INPUT
CRASH CONTROL INPUT
DCCT
DVM
RAMP GENERATOR
500A POWER SUPPLY
DVM
DATA AQUISITION PC
QUENCH DETECTOR
SAMPLE
SCHEMATIC OF ELECTRICAL MEASUREMENT APPARATUS

Fig. 2.

APPENDIX C
WIRE MEASUREMENT DATA

On the sheets to follow are summarized the data transmittal for measurement information from the vendor to BNL. It is only necessary for the vendor to supply the data as given in Appendix A. The vendor will coordinate with BNL the regular transmittal in electronic form.

Wire Mechanical Data

Wire ID
Wire twist direction (Left/Right)
Wire twist pitch (twists per inch)
Sharp bend test (Pass/Fail with comment)
Springback (degrees)
Surface condition (Pass/Fail with comment)
Cu/Sc ratio by chemical method (if used)
Comments

Wire Electrical Data

Wire ID
Date of tests
Run number
Ic at 5.6T
n at 5.6T
Iq at 5.6T
Jc at 5.6T
R(295)
RRR
Cu/Sc ratio by electrical method
Comments

Wire Production Data by Vendor

Wire ID
Wire length (feet)
Wire weight (lb.)
Diameter - Minimum
Diameter - Maximum
Diameter - Average
Diameter - Standard deviation
Diameter - Data points
Comments